

# **MODELING AND DESIGN OF AN ELECTRO-RHEOLOGICAL FLUID BASED HAPTIC SYSTEM FOR TELE-OPERATION OF SPACE ROBOTS**

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## **ABSTRACT**

In this paper a novel haptic interface is presented to enable human-operators to "feel" and intuitively mirror the stiffness/forces at remote/virtual sites enabling control of robots as human-surrogates. The proposed haptic interface is intended to provide human operators intuitive feeling of the stiffness and forces at remote or virtual sites in support of space robots performing dexterous manipulation tasks (such as operating a wrench or a drill). Remote applications are referred to the control of actual robots whereas virtual applications are referred to simulated operations. The developed haptic interface will be applicable to IVA operated robotic EVA tasks to enhance human performance, extend crew capability and assure crew safety. The novel device that is presented here employs Electro-rheological Fluids (ERF), which are electroactive polymers that change their viscosity when electrically stimulated.

## **KEYWORDS**

Haptic Interfaces, Telepresence, Space Robotics, Electro-rheological Fluids.

## **1. INTRODUCTION**

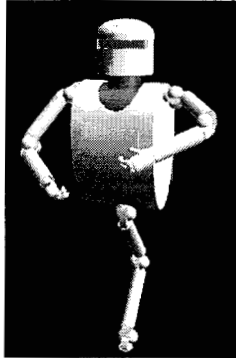
For many years, the robotic community sought to develop robots that can eventually operate autonomously and eliminate the need for human operators. However, there is an increasing realization that there are some tasks that humans can perform significantly better but, due to associated hazards, distance, physical limitations and other causes, only robots can be employed to perform these tasks. Remotely performing these tasks by operating robots as human surrogates is referred to as telepresence. In telepresence the operator receives sufficient information about the remote robot and the task environment displayed in a sufficiently natural way, that the operator would be able to feel the equivalent of physical presence at the remote site [1]. Haptic feedback is necessary for a telepresence system where physical constraints such as object rigidity, mass and weight, friction, dynamics, surface characteristics (smoothness or temperature) are mirrored to the human operator from the remote site [2].

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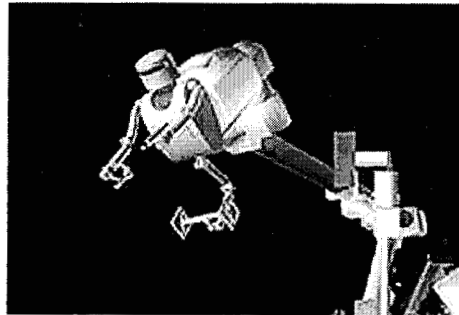
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Robots capability to operate as a surrogate human, which includes telepresent and performance of remote missions, has been recently implemented at NASA Johnson Space Center (see Figures 1 and 2) with the development of the novel space robot called Robonaut (see Figure 1). This robot is capable of performing various tasks at remote sites [3] and serve as a robotic astronaut on the International Space Station, providing a relatively fast response time and the ability to maneuver through areas too small for the current Space Station robots. Robonaut is developed to support high-payoff EVA tasks and to provide "minuteman"-like responses to EVA contingencies. The Robonaut is designed as an anthropomorphic robot, similar in size to a suited EVA astronaut and as a telepresence system that immerses the remote operator into the robot's environment [3].



**Figure 1.** Robonaut



**Figure 2:** Robonaut Secured to Mount

Robonaut was designed so that a human operator who is wearing gloves/suit with sensors can control it. In the case of the Robonaut project, the human operator must control nearly fifty individual degrees of freedom. If the user is to control the robot motions in a naturally perceived way, an interface device must be provided which is capable of determining what the user is doing without interfering with his/her motion or encumbering his/her body. Unfortunately, due to unavailability of force and tactile feedback capability in the control suit/glove, the operator determines the required action by visual feedback, i.e. looking at the Robonaut action at the remote site. This approach is ineffective and is limiting the potential tasks that Robonaut can perform. To date, there are no effective commercial unencumbering haptic feedback devices for the human hand. Current "hand master" haptic systems, while they are able to reproduce the feeling of rigid objects, present great difficulties to emulate the feeling of remote/virtual stiffness. In addition, they tend to be heavy, cumbersome and usually they only allow limited operator workspace.

This paper presents the development of haptic interfacing mechanism that will enable a remote operator to "feel" the stiffness and forces at remote or virtual sites. These interfaces will be based on novel mechanisms that were conceived by JPL and Rutgers University investigators, in a system called MEMICA [4]. The key aspect of the MEMICA system is a miniature electrically controlled stiffness (ECS) element that mirrors the stiffness at remote/virtual sites. The ECS elements make use of electro-rheological fluid (ERF), which is an electroactive polymer (EAP), to achieve this feeling of stiffness. The ECS elements will be placed at selected locations on an instrumented glove to mirror the forces of resistance to motion at the corresponding locations at the robot hand. Forces applied at the robot end-effector due to a compliant environment will be reflected to the user using this ERF device where a change in the system viscosity will occur proportionally to the force to be transmitted. The MEMICA system consists also of force feedback actuation tendon (FEAT) elements, which employ other type of actuators to mirror forces induced by active elements at the remote or virtual site. The description of FEAT elements is outside the scope of this paper.

## 2. SYSTEM OVERVIEW

### 2.1 Electro-Rheological Fluids (ERFs)

Electro-rheological fluids (ERFs) are fluids that experience dramatic changes in rheological properties, such as viscosity, in the presence of an electric field. The fluids are made from suspensions of an insulating base fluid and particles on the order of one tenth to one hundred microns in size. The electro-rheological effect, is thought to arise from the difference in the dielectric constants of the fluid and particles. In the presence of an electric field, the particles, due to an induced dipole moment, will form chains along the field lines. This induced structure changes the ERF's viscosity, yield stress, and other properties, allowing the ERF to change consistency from that of a liquid to something that is viscoelastic, such as a gel, with response times to changes in electric fields on the order of milliseconds. A good review of the ERF phenomenon and the theoretical basis for their behavior can be found in [5].

In this work, the electro-rheological fluid LID 3354, manufactured by ER Fluid Developments Ltd., has been used [6]. LID 3354 is an electro-rheological fluid made up of 35% by volume of polymer particles in fluorosilicone base oil. It is designed for use as a general-purpose ER fluid with an optimal balance of critical properties and good engineering behavior. Solid and liquid are density matched to minimize settling. LID 3354 can be used in suitable equipment wherever electronic control of mechanical properties is required, such as in controlled dampers, actuators, clutches, brakes and valves. Its physical properties are: density:  $1.46 \times 10^3 \text{ kg/m}^3$ ; viscosity: 125 mPa.sec at 30°C; boiling point: > 200°C; flash point: >150°C; insoluble in water; freezing point: < -20°C.

### 2.2 MEMICA and ECS Elements

As mentioned earlier, MEMICA is a haptic interface system that consists of a glove equipped with a series of electrically controlled stiffness (ECS) elements as it is schematically shown in Figure 3. Each finger needs to be equipped with one or more of these elements to maximize the level of stiffness/force feedback that is "felt" by the operator as he/she applies activation pressure. Miniature electrically controlled stiffness (ECS) elements are responsible for mirroring the level of mechanical resistance to the applied forces by the remote or virtual robots at specific joints/points. The element stiffness is modified electrically by controlling the flow of an electro-rheological fluid (ERF) through slots on the side of or embedded in the piston (Figure 4). The ECS element consists of a piston that is designed to move inside a sealed cylinder filled with ERF. The rate of flow is controlled electrically by electrodes facing the flowing ERF while inside the channel.

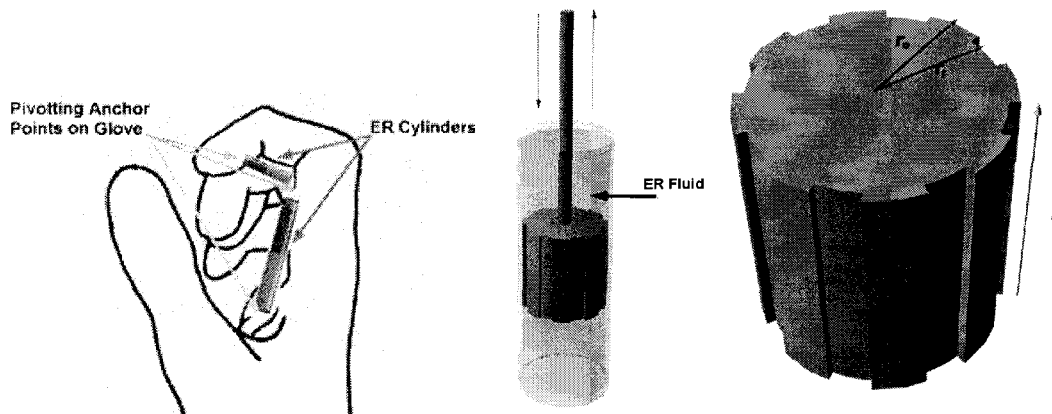


Figure 3. MEMICA System

Figure 4. ECS Element and Close-Up View of the Piston

To control the “stiffness” of the ECS, a voltage is applied between electrodes that are facing the slot and the ability of the liquid to flow is affected. Thus, the slot serves as a liquid valve since the increased viscosity decreases the flow rate of the ERF and varies the stiffness that is felt. To increase the stiffness bandwidth, ranging from free flow to maximum viscosity, multiple slots are made along the piston surface. To wire such a piston to a power source, the piston and its shaft are made hollow and electric wires are connected to electrode plates mounted on the side of the slots. The inside surface of the ECS cylinder surrounding the piston is made of a metallic surface and serves as the ground and opposite polarity. A sleeve covers the piston shaft to protect it from dust, jamming or obstruction. When a voltage is applied, potential is developed through the ERF that flows along the piston channels and its viscosity is altered. As a result of the increase in the ERF viscosity, the flow is slowed significantly and increases the resistance to external axial forces.

### 3. MODELING AND DESIGN OF ECS ELEMENTS

In order to optimally design and control the ECS device, an analytical mathematical model was developed. This model calculates the forces felt by an operator as a function of the piston geometry, applied voltage and the motion characteristics imposed by the operator. In this section, a summary of the model equations is presented and two cases are distinguished: static and dynamic.

It can be shown that the static reaction force  $F_{R,s}$  is given by:

$$F_{R,s} = NC_s L \left[ \left( 2 + \frac{2\theta}{\ln\left(\frac{r_o}{r_i}\right)} \right) V - (2\Delta r + \theta(r_o + r_i)) E_{ref} \right] \quad (1)$$

where:  $N$  is the number of channels,  $C_s$  is the constant associated with the static yield stress,  $L$  is the channel length,  $\theta$  is the angular width of channel,  $r_o$  is the outer radius,  $r_i$  is the inner radius,  $\Delta r$  is the channel width ( $r_o - r_i$ ) (see also Figure 4 where the geometric parameters are defined.),  $V$  is the applied voltage and  $E_{ref}$  is the constant reference field.

The following equation can be developed to express the total dynamic reaction force  $F_{R,d}$ :

$$F_{R,d} = \left( \frac{\pi r_o^2}{\frac{N\theta}{2}(r_o^2 - r_i^2)} \right) NL \left[ \left( C_d - C_v \frac{v}{\Delta r} \right) \left( \frac{\theta}{r_o} + \frac{\theta}{r_i} + \frac{2}{r_i} - \frac{2}{r_o} \right) \frac{V^2}{\left( \ln\left(\frac{r_o}{r_i}\right) \right)^2} + \mu_o \left( 2 + \theta \left( \frac{r_o + r_i}{\Delta r} \right) \right) v \right] - \rho L \left( \pi r_o^2 - \frac{N\theta}{2}(r_o^2 - r_i^2) \right) a \quad (2)$$

where the additional variables are:  $C_d$ , the constant associated with dynamic yield stress;  $C_v$ , the constant associated with viscosity;  $v$ , the velocity;  $\mu_o$ , the dynamic viscosity with no electric field applied;  $\rho$  the density;  $a$ , the acceleration.

The analytical equations (1) and (2), will be used to evaluate the effects on the reaction forces felt by the user when various geometric and input parameters are changing. The results from this study are very important for the design of the ECS elements.

Human studies have shown that the controllable maximum force that a human finger can exert is between 40 and 50 N [2]. However, maximum exertion forces create discomfort and fatigue to the human operator. Comfortable values of exertion forces are between 15 to 25% of the controllable maximum force exerted by a human finger. Hence, the design objective is

to develop an ECS element that will be able to apply a maximum force of 15N to the operator. We are primarily interested in the dependence of the reaction forces from the ECS when the following parameters are changing: voltage applied  $V$ , motion characteristics imposed by the user such as the velocity  $v$ , and acceleration  $a$ , and geometric characteristics of the piston such as geometry of the channel defined by the inner and outer diameters  $r_i$  and  $r_o$ , and the angle of the channel  $\theta$ . Therefore in our study, it is desired to find out the ranges of values for these parameters that will result in the desired maximum force output of 15N.

The parameters related to the fluid ERF LID 3354, shown in Table 1, have been determined from the manufacturer's specifications [6]. The default geometric parameters of the ECS element shown in Table 2, have been determined from the dimensions of commercially available sensors and electronic equipment that will be used for measuring and actuating the device and also by manufacturing and machinability constraints. In the first prototype, that is presented in this work (see Section 4), no effort for miniaturization was made since the goal was to prove the concept that ERFs can be used to create haptic feedback. The default values for motion characteristics were selected based on the maximum velocities and accelerations that a human finger can develop (see Table 3).

**Table 1.**  
ERF LID 3354 Parameters

$C_{dl}$	0.00026 Pa.m <sup>2</sup> /kV <sup>2</sup>
$C_v$	0.198 E-7 Pa.sec. m <sup>2</sup> /kV <sup>2</sup>
$C_s$	2.77 Pa.m/kV
$E_{ref}$	1,090 kV/m
$\mu_0$	0.125
$\rho$	1460 kg/m <sup>3</sup>

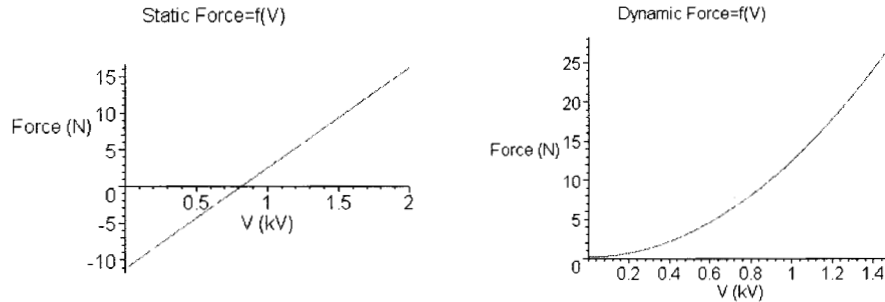
**Table 2.**  
Geometric Parameters

$L$	0.0254m
$r_i$	0.011316m
$r_o$	0.012065m
$\Delta r$	0.000749m
$N$	12
$\theta$	0.47 rad (27°)

**Table 3.**  
Motion Characteristics

$a$	0.01m/s <sup>2</sup>
$v$	0.1m/s

Voltage is the principal parameter of interest in this study since it will be used for controlling the compliance of the ERF. It is desired to calculate the maximum voltage that is needed for achieving a reaction force of 15N. Setting the default values in Equations (1) and (2) and changing the voltage the force has been calculated and is shown in Figure 5. As expected the relationship of the force to the voltage is linear in the static case and parabolic in the dynamic case. A voltage of approximately 2kV is needed in the static case to achieve the desired force of 15N. In the dynamic case the desired force output of 15N is reached using 1kV. The need of high voltage using the ERF's was expected. However, as it is demonstrated in Section 4, a low power circuit has been developed to generate the high voltage with a very low current.



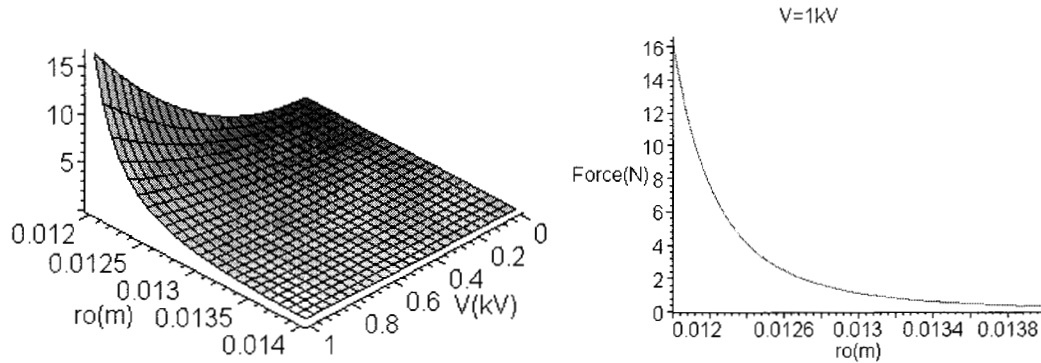
**Figure 5.** Force as a Function of Voltage

A similar parametric study revealed that the reaction force is almost independent of the velocity and acceleration imposed by the user. This is due to the fact that the velocity and acceleration contributions in the reaction force are much smaller than the effect of the voltage related term.

The piston geometry is another important factor that affects the reaction force felt by the user. In the results presented in this section, the outer diameter of the piston changes from 0.012m to 0.014m while the voltage changes from 0 to 1kV. All other parameters take the default values shown in Tables 1, 2 and 3. The calculated reaction forces are shown in Figure 6. It is clearly seen that as the outer diameter increases the reaction force decreases dramatically. On the other hand as the outer diameter approaches the value for the channel inner diameter the reaction forces take infinite values. This shows that the thinner the piston channels the larger the reaction force is and hence the required voltage can be reduced.

In a similar way, the channel angle changed from 0 to 0.5 radians and the force was calculated. Under a certain minimum value of  $\theta$ , the reaction force drops dramatically. Also there is a maximum limit for  $\theta$  after which the reaction force is constant. Therefore optimal values for  $\theta$  are around 0.4 radians (i.e. 30 degrees).

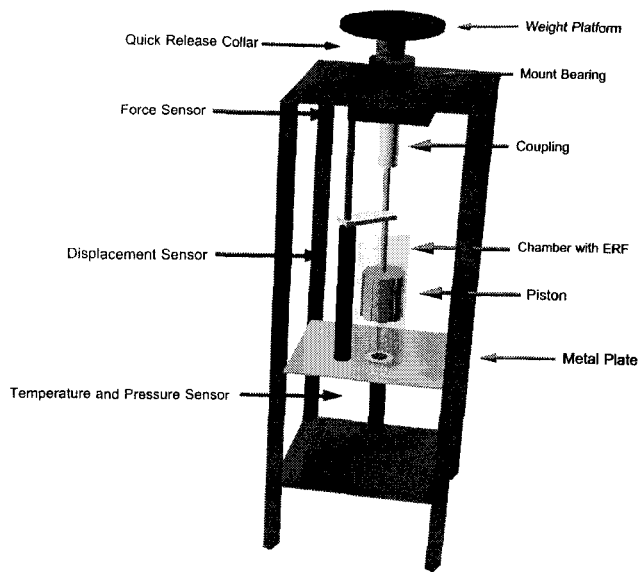
The parameters  $N$  and  $L$  affect in a linear way the reaction force. Increasing these parameters increases the force for a given voltage. However, the dimensions of the piston limit  $L$  and the number of channels  $N$  is limited by the values of  $\theta$ .



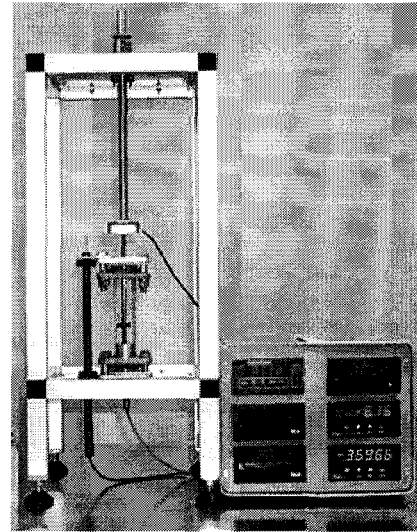
**Figure 6.** Force (N) as a Function of the Outer Diameter  $r_o$  and Voltage  $V$

#### 4. EXPERIMENTAL SYSTEM

In order to test the concept of controlling the stiffness with a miniature ECS element, a larger scale test-bed has been built at the Rutgers Robotics and Mechatronics Laboratory. This test-bed, that is shown in Figures 7 and 8, is equipped with temperature, pressure, force and displacement sensors that will be used for monitoring the ERF's state. There are six system parameters that are measured during experimentation: voltage, current, force, displacement, pressure and temperature. All sensor signals are interfaced directly to Analog-to-Digital boards located in a Pentium II PC and are processed using the Rutgers WinRec v.1 real time control and data acquisition Windows NT based software. In addition, all sensors are connected to digital meters located in the interface and control box. For the sensors, excitation voltages are supplied by five volts from the PC or by the meter provided with the sensor itself. The ERF power system is a small supply circuit originally designed for night vision scopes [7]. This power supply is capable of producing 4.5-KV from a standard 9-V battery. By modifying this circuit to produce a PC adjustable straight DC voltage, linear control of the viscosity is implemented with programmed software control. This power system allows for portability in later prototypes. All the interface and control circuitry are housed in a portable ventilated enclosure.



**Figure 7.** Experimental Test-bed



**Figure 8.** Actual Prototype System

## 5. CONCLUSIONS

Using electroactive polymers or smart materials can enable to develop many interesting devices and methodologies to support the need for haptic interface in such areas as automation, robotics, medical, games, sport and others. The authors studied the use of Electrorheological fluids to allow “feeling” the environment at remote or virtual robotic manipulators. A new device was introduced for operators to sense the interaction of forces exerted upon a robotic manipulator that is being controlled. An analytical model was developed and experiments are being conducted on the so-called electrically controlled stiffness (ECS) element, which is the key to the new haptic interface. A scaled size experimental unit was constructed and allowed to demonstrate the feasibility of the mechanism.

## 6. ACKNOWLEDGEMENTS

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